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Power and Energy Computational Models for the Design and Simulation Of Hybrid-Electric Combat Vehicles

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ABSTRACT

This paper describes the work being performed under the RDECOM Power and Energy (P&E) program (formerly the Combat Hybrid Power System (CHPS) program) developing hybrid power system models and integrating them into larger simulations, such as OneSAF, that can be used to find duty cycles to feed designers of hybrid power systems. This paper also describes efforts underway to link the TARDEC P&E System Integration Lab (SIL) in San Jose CA to the TARDEC Ground Vehicle Simulation Lab (GVSL) in Warren, MI. This linkage is being performed to provide a methodology for generating detailed driver profiles for use in the development of vignettes and mission profiles for system design excursions.

Keywords: Modeling and Simulation, Hardware-in-the-loop, Real-time systems

INTRODUCTION

The increasing electrification of the battlefield is precipitating new challenges for combat vehicle power system designers. Soon, with the advent of both electric offensive and defensive weapons, the pulse and continuous loads due to the 'auxiliary' equipment will rival that of the mobility element, traditionally the driving requirement for sizing the components of the power train. Systems currently in the laboratory - including electromagnetic (EM) guns, electro-thermal chemical (ETC) guns, electric armor, lasers and other forms of directed energy weapons and survivability systems - are nominally pulse systems, but they require significant continuous power to 're-load' (i.e., re-charge their pulse forming networks). Their capability and utility is directly related to the ability of the continuous power system to maintain the pulse system at or near full state-of-charge at all times.

In addition to the increase in power and energy requirements due to on-board vehicle loads there is also an increase in the power and energy needs to support off-vehicle systems. For example, dismounts are using more electrical energy and power in the form of batteries and small electrical systems that periodically require re-charge.

It is clear that the ability to efficiently supply electrical energy and power on the battlefield to support emerging technologies will markedly dictate the future force's capabilities. With a mechanical drive system the electrical energy required to support new and emerging combat technologies requires the development and design of both a large auxiliary power unit (APU) for electrical power generation and a large transmission and mobility drive train to support vehicle mobility and propulsion.

The full capabilities of the next generation combat vehicle systems can be efficiently and fully realized using hybrid electric drive systems where the mobility/propulsion elements of the system and the offensive/defensive armaments

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14. ABSTRACT
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share common continuous and pulse electric power producing hardware [1]. Hybrid power systems allow the vehicle to combine mobility and auxiliary systems power and energy needs so that a single power system supplies all the power to the vehicle. In this manner the vehicle's mobility power can be used to drive auxiliary system electrical loads and vice-a-versa.

Hybrid power technologies also enable creative application of battlefield power management and intelligent power management both of which can be implemented to reduce the fielded footprint and logistics footprint of the fighting force. This has a number of implications on vehicle design and eventual deployment on the battlefield and will require extensive testing and validation before actual vehicles are put on the battlefield. In particular, modifications to the tactics and techniques will have to be examined due to the fact that power and energy with hybrid systems are mobile assets that can rapidly be moved from point-to-point on the battlefield under the control and direction of the intelligent power management system. It also can reduce the need for dedicated mobile generators on the battlefield since every vehicle on the battlefield is potentially a mobile generator.

In order to design the next generation of combat vehicles, to test the systems, and to make informed decisions about the force structure it is necessary to have standard methodologies for sizing the power system and its components. One item that is sorely lacking within the combat vehicle design community is a standard driving/usage profile that can be used by all designers to perform system design and size excursions. In the commercial world there are a number of driving schedules that are used to compare different power train alternatives and to assist in the design of the vehicle. Driving schedules such as the Federal Urban Driving Cycle (FUDC) [2] can be used to perform design trade studies and to develop objective metrics with which to compare different designs and topologies. There is no corresponding standard Army mission profile that combat vehicle designers can rely on for objective design trade studies. This problem is compounded if you add in the requirement to power primary survivability and lethality systems.

Because of the capability offered by a hybrid electric system to recapture, store and compress electrical energy the design of the system and the development of the requirements for the system needs to be done in a dynamic environment that closely emulates the ultimate use environment. In recognition of this the US Army RDECOM TARDEC [3] has supported the development of a series of detailed power system and vehicle models that can be inserted into large scale force-on-force simulations where experiments can be performed to examine the effectiveness of the new systems on the virtual battlefield. The suite of tools assists in the automated design of hybrid electric vehicles, projects the battlefield power usage of various size Army units and can be used to develop objective mission profiles for use in the development of vehicle power systems. The suite of tools is built around a flexible power system description that can be used at varying levels of fidelity in a range of different applications from non-real-time design and analysis studies to real-time embedded systems for use in operator-in-the-loop and hardware-in-the-loop experiments to force-on-force simulations such as OneSAF, CASTFOREM.

The tools are developed in the MATLAB/Simulink environment which has a well defined programming API allowing us to easily extend the system. The well documented and flexible API supports embedding the power system tools into other simulations and models developed in other environments. For example, high resolution multi-body vehicle models are usually developed in packages such as SimCreator which have much more capabilities and tools for the solution of the DAEs describing the dynamics of the vehicle than does the Simulink environment. We are developing an open interface that will allow the power system models to be embedded in these simulations.

This paper reviews the progress to date on developing the tools for hybrid power system design and analysis. Section 2 discusses the Engineering Toolbox and describes the API that allows the models to be embedded in other simulations. Section 3 discusses the Power Budget model and the technology we are embedding in it to allow it to be used to project battlefield power and energy usage.

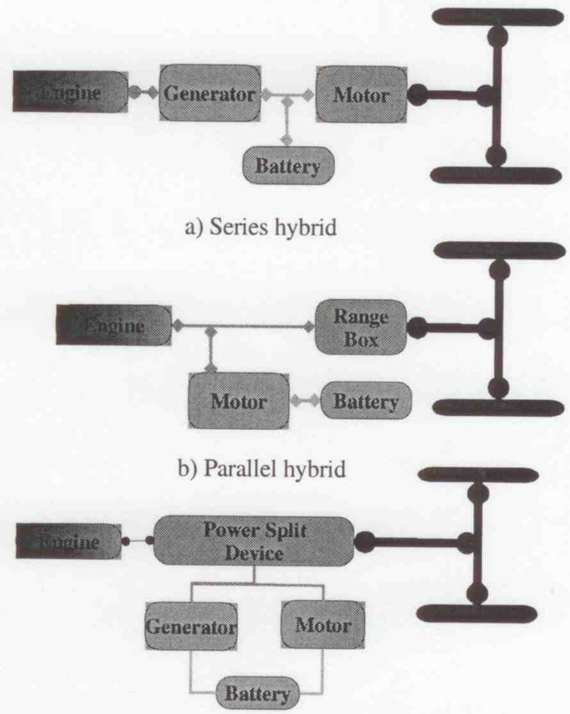
ENGINEERING TOOLBOX

Hybrid power systems can take on a number of different configurations and component topologies ranging from pure series architectures in which all mobility power on the system is derived from the electrical system and the engine does not directly drive the wheels, to parallel configurations where there are both electrical and mechanical pathways from the engine to the drive sprockets. Any tool that purports to analyze hybrid drive alternatives must be flexible enough to

allow the user the ability to construct arbitrary electrical/mechanical topologies. The library that has resulted from the effort is composed of basic mechanical and electrical components such as conventional gears, planetary gears, and electrical machines which are dragged-and-dropped within the graphical Simulink environment to build the model. Interactions between the components are described by the graphical connections that mimic the physical connections between the components. This means the models can be intuitively organized in a manner similar to the physical construction of the system.

Figure 1 contains notional layouts of the power systems that have been simulated with the tools contained in the toolbox. The power trains include purely electrical power systems as well as purely mechanical power systems and the various hybrid systems that span the range between the two extremes. As a concrete example of the use of the model for power system simulation, which also happens to be the system used to define the standard interfaces, we consider the series hybrid design shown in **Figure 2**. This system uses a diesel genset to provide continuous power through an inverter to an unregulated high voltage DC bus. A battery pack sized to provide silent watch and silent mobility functions is attached directly to the bus and maintains bus voltage at approximately 600 Volts.

Attached to the high voltage bus are two independent induction motors for the left and right sprocket drives capable of providing 300 kW of continuous power and over 900 kW of burst power for braking and acceleration functions. A brake or dump resistor is also attached to the bus to protect it from over-



a) Series hybrid

b) Parallel hybrid

c) Electrical continuously variable transmission hybrid

Figure 1 – Hybrid vehicle architectures that have been modeled using the Engineering Toolbox formalism.

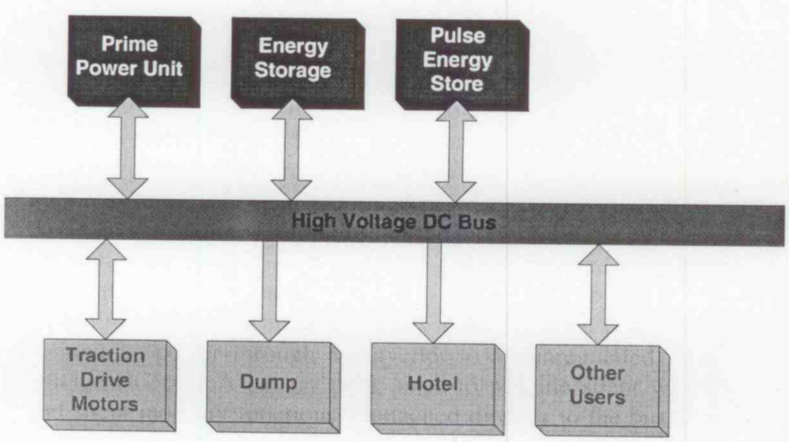


Figure 2 – Layout and components of the series hybrid power system used in the CHPSPerf model

voltage conditions that might arise due to heavy braking or long duration regeneration events.

CHPSPerf [4] is the integrated power-system performance component of the toolset being developed by the P&E team. It is an outgrowth and extension of the IAT developed IMPACT toolbox [5, 6]. As such it retains all the capabilities contained within the toolbox along with new capabilities and features that were added under the P&E program to make it accessible to a wide spectrum of users. Additionally, the capabilities of the basic system were expanded to include physical phenomena such as thermodynamic and thermal interactions along with the electrical dynamics of the power system.

The original concept underlying the toolbox was to develop a set of building block

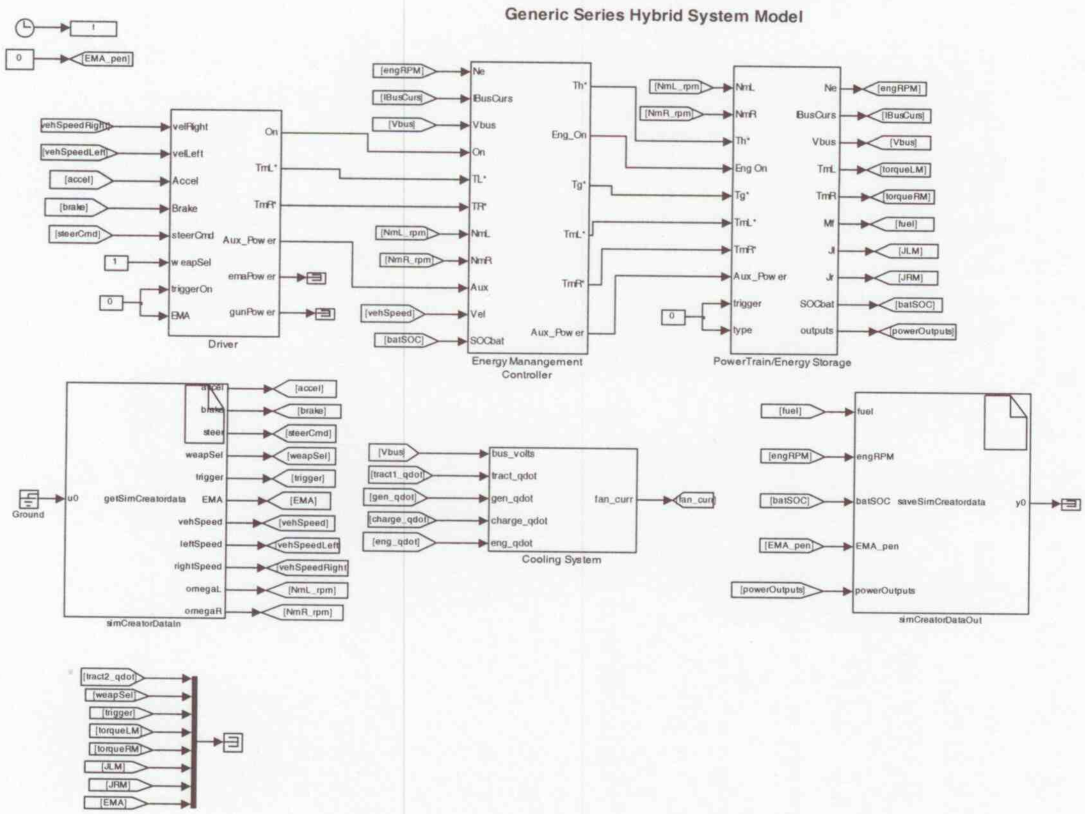


Figure 3 – Top-level Simulink model of the CHPSPerf model showing S-function interface to external programs (simCreatorDataIn and simCreatorDataOut).

components with which to rapidly construct and analyze new power system architectures. Within the Simulink graphical editing environment the toolbox makes the modeling of complex system relatively straightforward. With this approach, one can either perform trades examining the full power system or alternatively individual components can be modeled and studied in detail.

This method of using the toolbox has its advantages and has proven to be useful in developing system architectures for a number of different vehicles. However, use of the model is usually restricted to individuals with an extensive working knowledge of both the toolbox and Simulink. To remedy this situation a number of steps are being taken to enhance and make it more suitable for non-Simulink users and for developers working in non-Simulink environments. These steps were taken to relieve the user of much of the task of building up a power system from scratch and from the burden of learning the Simulink environment and its API.

First a decision was made to develop a set of generic power system architectures. Using lessons learned during the development of system simulations of various power system architectures, has allowed us to isolate those features of the model that are common across a wide class of analyses. Using these common features we have or are contemplating the development of generic models of: 1) a series hybrid, 2) a before the transmission parallel hybrid, 3) a after the transmission parallel hybrid, 4) an electrically continuously variable transmission. It should be noted that these generic models do not replace the underlying toolbox but rather augment it for those users with a need for fast turnaround

analyses of new architecture concepts or are interested in embedding a power system in other environments and simulations.

Second it was decided to produce both standalone executable versions of the generic simulations as well as static link library versions of the models that can be included in any environment that has a 'C'-language calling interface. This was done for two reasons: 1) executable versions run much faster than their interpreted counterparts and 2) a clean 'C' interface hides the underlying complexity of the simulation environment. Both versions of the compiled simulations use the rapid prototyping capabilities of the Simulink environment wherein one can take the block diagram and convert it into 'C'-language code. Additionally, we use S-functions to define the calling interfaces to the power system library routines. Although the Simulink and RTW interfaces are well-defined, a full interface API, wherein the data elements and their locations are fully exposed using the RTW API, provides more opportunity for errors so we have developed a limited API that exposes the minimum elements to the simulation environment. In general full access to the complete data structures is not necessary instead exposing a small subset of the information to the external world is sufficient for most practical applications. Additionally, developing an interface using S-functions removes the dependence of the code on the interface provided by Simulink so that if in the future we want to change environments this can be accomplished with a minimum of re-work on the API.

Each of the components shown in the notional layout of **Figure 2** is modeled in the CHPSPerf series hybrid simulation, the top level Simulink diagram of which is shown in **Figure 3**. For the purpose of interfacing to the GVSL and other uses of the power system the subsystems of primary interest to the vehicle are contained in the blocks labeled as Power Train/Energy Storage, Vehicle, Thermal management and Energy management in **Figure 3**. A summary description of the underlying models is given below.

- **Vehicle** – For the present capabilities description the vehicle mobility loads are imposed using multi-body dynamics models. There are currently two models being integrated into the system. One is Simulink based while the other is a model based on SimCreator. The SimCreator model and its interfaces are being developed to interface to the crew station at the Ground Vehicle Simulation laboratory (GVSL). The interface, shown in **Figure 3** as the two blocks ***simCreatorDataIn*** and ***simCreatorDataOut***, consists of a specification of the direction of the torques and information (torque/speed) flow between the vehicle model and the power system model. The interfaces agreed to right now the power system passes torque information over to the vehicle system and the vehicle system passes speed information back across to the power system.

- **Motor/Generator** – The vehicle uses induction machines for both the traction motors and the generator. Additionally, the cooling fan is also an induction machine. The traction motors and the generators in the simulation are 3-phase induction machines. Because of the relative importance of the mobility system in the overall power system efficiency (accounting for upwards of 90 percent of the total energy consumption during a typical mission) we have expended a substantial effort in developing reliable and accurate machine models for this aspect of the system. There are two electrically steady mechanically dynamic machine models and one fully dynamic (electrical and mechanical) machine model available for the simulation.

- **Battery** – The battery in the simulation is based on the Li-ion cell model proposed by SAFT. In this model, the battery is represented by a capacitor/resistor network with the values of the various elements in the system derived from experimental measurements. The single cell model was subsequently modified to account for multiple series/parallel combinations of cells.

- **Engine** – There are two levels of complexity one can use in describing the engines in the model. The first level and that which is implemented in the GVSL crew station is the simple table lookup of the torque and fuel consumption properties of the engine. The engine in this case includes no dynamics and is modeled purely as a table look-up. Two tables are required for the model:

    - **Torque table** – a two-dimensional table with torque as a function of 'throttle' position (actually for a diesel engine the fuel rail position) and engine speed, and

- **Specific fuel consumption table** – a two dimensional table with sfc as a function of 'throttle' position and engine speed.

- In addition to the simple table lookup model, we have developed a package of thermodynamic, fluid and thermal elements which can be linked together to give a more detailed representation of the dynamics of engines.

- **Dump Resistor** – The dump resistor is modeled as a resistor with a resistance that varies from zero to its maximum value with a linear gain.

- **Thermal Management** – The thermal management system is actually a set of components which can be linked together to form a closed or open loop thermal control and management system. The major components included in the model used in the vehicle simulator are:

  - **Tank** – The tank is a constant volume system that accumulates mass and energy. The time dependent mass and energy equations are solved for the tank fluid and exit fluid temperatures.

  - **Heat Exchanger** – This model uses a fixed effectiveness to calculate the thermal performance of a heat exchanger given the inlet properties for the two fluids. Parameters for the model include the effectiveness and the flow areas of the two flow streams. Inputs to the model are the inlet temperatures for the respective streams and the fluid properties for the two streams including their density, viscosity, thermal conductivity and specific heats.

  - **Fan** – The load on the induction motor is calculated using the pressure drop properties of the radiator and system ductwork. A controller varies the speed (and hence flow rate and power consumption) of the fan based on cooling fluid temperatures in various parts of the power system.

- **Converter** – The converter model is based on a loss model that accounts for both passive component (capacitor) and active switching losses. Calculation of the passive losses is performed using the equivalent series resistance of the capacitor of the system while the active losses are calculated by calculation of the diode and switch losses during turn-on, turn-off and steady-state standoff. The losses for the system can be put into a form per switch/diode pair.

POWER BUDGET MODEL

The objective of the Power Budget Model (PBM), schematically shown in **Figure 4**, is to provide combat vehicle designers and Army decision makers with a tool to project the power demands and power usage of each entity on the battlefield – thus providing the user community with a tool to assist them in making informed decisions concerning force structure and vehicle designs. The PBM provides a power estimation and control capability at both the vehicle level and at the unit level that aggregates multiple vehicles and multiple players. At the vehicle level it provides the capability to calculate the automotive performance along with the capabilities of the power supply to provide timely and sufficient energy to each load (both on and off vehicle) of the system.

The PBM is being developed and released in phases. The Phase 0 version of the tool is the existing power system modeling tool CHPSPerf [4] which was discussed in the preceding section. This model has the capability to calculate the mobility and thermal management power demands of a single vehicle and, through a total auxiliary power input variable, the non-mobility loads of the system. The next version of the PBM, Phase I, is currently being tested and extends the existing vehicle-level model by including at a minimum the interfaces and elements shown in **Figure 4**. This model takes as input events such as map waypoints, vehicle speeds, weapon fires, armor engagements, and commander and driver actions, i.e., a mission profile, and applies the events to the power and mobility systems to ascertain the performance of the power system.

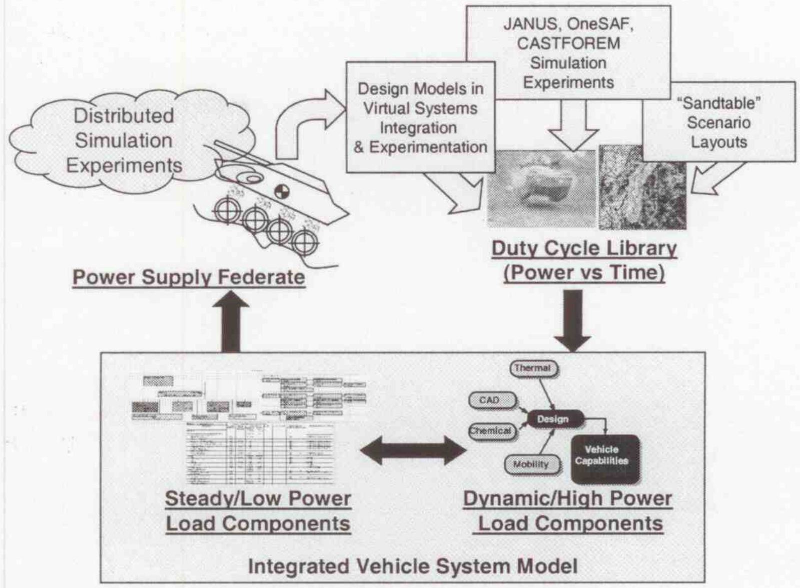


Figure 4 - Power Budget Model – Final Version

For Phase I the tool has the capability of using events, or mission profile, taken from CASTFOREM runs. The data from representative CASTFOREM simulations is being used to develop a strategy for automated transferal of information between the two simulations and for examining the CASTFOREM data to ascertain its applicability to the PBM simulations. Information that is needed for the power system model includes:

- Vehicle location – either a one dimensional path with corresponding slope information or a full map description with individual waypoints on the map.
- Vehicle speed at given waypoints – these activities give the mobility request for the vehicle that the driver is requesting.
- Road surface – terrain type information that can be used to infer the rolling resistance of the terrain and a measure of the terrain roughness that can be used to predict the power and motion transmitted to the crew station.
- Commander/gunner events – weapons fires and activation of various systems on board the vehicle. This is one of the more difficult items to extract from non-real-time simulations with little or no feedback of information to the driver/commander. The weapons fires are fairly easy to extract from the runs but other auxiliary systems that are activated and drawing power at any given time within the scenario are more problematic. One option that is being investigated for determining what systems are activated and what systems are not activated is to define packages of auxiliary equipment that are activated during certain events that occur during the simulation.

The CASTFOREM calculations are non-real-time calculations without a driver or commander in the loop and with only serial feedback of the vehicle with the virtual combat environment. That is CASTFOREM assumes a set of vehicle performance characteristics and the capability of vehicle to perform certain road maneuvers. To the extent that the vehicle performs at the level assumed in CASTFOREM then the results and the generated mission are representative. The major issue with this approach is the time sequencing of events in the case where the vehicle cannot perform at the level assumed in the CASTFOREM calculation. For example, if the vehicle in the CASTFOREM simulation can make a better speed than the vehicle in the detailed simulations then some of the waypoints and events won't occur at the correct time which could have an impact on the vehicle's and the force's performance.

Although there are some shortcomings to the use of the CASTFOREM calculations they have allowed us the opportunity to get a good start on defining quantities that are needed for the calculations and to begin the definition of the mission duty cycles. The major advantage of using CASTFOREM in this context is the level of the forces in the simulation. A single calculation can yield mobility and power usage statistics on hundreds of different vehicles.

Phase II of the PBM is an interactive driver/commander in the loop capability where a single driver controlled 'vehicle' can interact with computer generated forces or with other systems in a small virtual world. A demo version of this capability was developed that works with a TARDEC developed on-board training simulation system. This capability avoids some of the limitations of the CASTFOREM based approach in that a driver/commander is providing inputs to the system based on feedback from the environment and the vehicle.

Finally Phase III of the simulation connects the crew station contained in the GVSL to the hybrid power system in the system integration laboratory (SIL). The P&E SIL and the GVSL motion platform are being integrated into a system for getting realistic driver inputs onto the power system at the SIL.

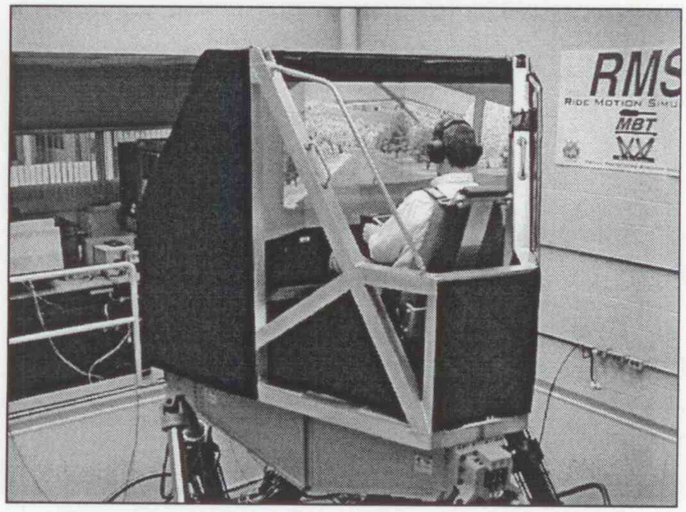


Figure 5 – Ride Motion Simulator at TARDEC's Ground Vehicle Simulation Laboratory (GVSL)

The TARDEC Ground Vehicle Simulation Laboratory (GVSL) is a research laboratory located in Warren, MI that contains a high-performance, six degree of freedom simulator, **Figure 5**, and a networked distributive simulation environment that is capable of recreating military operations on harsh, off-road terrain. The six DOF simulator is being equipped for this project with a developmental crew station being developed by TARDEC. The crew station development includes an embedded simulation system that is capable of presenting a realistic simulation environment on-board for the purposes of training and for the purpose of simulating external entities during limited testing and demonstrations.

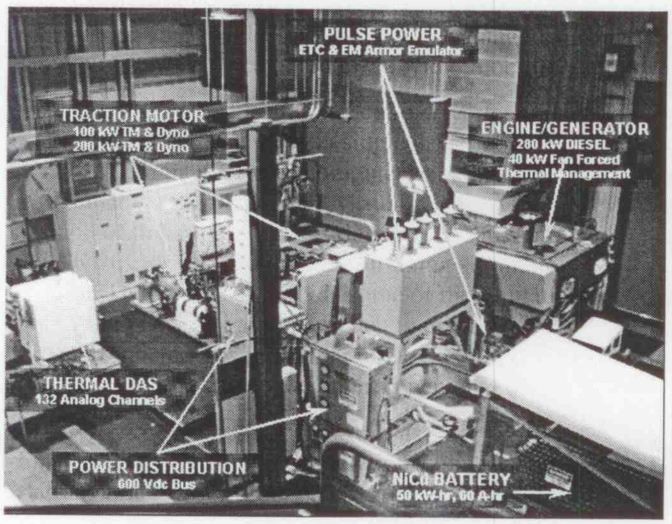


Figure 6 – The SIL and the major subsystems included in the facility

The TARDEC Power and Energy Systems Integration Laboratory (SIL) is a re-configurable hardware in the loop test facility for hybrid vehicle systems. **Figure 6** shows the SIL with each of the major subsystems highlighted. The major systems contained in the SIL can be classified in two broad categories, vehicle emulation equipment and subsystems, i.e., those subsystems which emulate the vehicle's power system and facility support equipment and subsystems, i.e., those subsystems that emulate the loads due to the vehicle's interactions with its environment.

The SIL emulates the mobility, hotel and weapons power for a ~15-ton combat vehicle. The emulated vehicle includes both continuous power drains such as mobility loads as well as pulse power drains such as pulse laser weapon systems. The power system is a series hybrid design with an unregulated DC bus with the battery pack providing the bus voltage. Specifically, the power system in the SIL contains:

- Prime Power -The prime power subsystem provides all the continuous power needs for the vehicle. For the SIL and the NCV sizing of the prime power system was driven by the requirement to maintain a road speed of ~60-70 mph. The prime power subsystem is comprised of a 280 kW Caterpillar 3126 diesel engine, a UDLP 85 series 750V, 350kW generator and a 100-150kW inverter
- Traction Subsystem - The traction subsystem is composed of two back-to-back motors– the vehicle's traction motor and the facility dynamometer. In the current SIL the dynamometer and the traction motor are identical. The dynamometer represents the resistance the vehicle "sees" due to loads imposed on the vehicle due to ground rolling resistance, aerodynamic drag, gravity loads and any tow loads. For example, the dynamometer provides positive torque on the motor to simulate downhill conditions in which case the motor generates recovering energy. Both the traction motor and the dyno are induction motors. The traction and dyno motors are coupled via a shaft that includes both torque and speed sensors.
- Battery Bank – The battery bank sets the bus voltage for the SIL and is also used to provide load leveling for acceleration, hill climb and other short duration intense events that cannot be fully provided for by the engine. The battery provides all instantaneous power to the bus. The battery pack was sized to provide both silent watch and silent mobility functions for the vehicle. Although the eventual battery pack for the vehicle will be a variation of Li-ion batteries we have chosen to use NiCd batteries for the SIL because of their more ready availability. The battery bank is composed of two sets (trays) of 1.2 V, 60 Ah NiCd cells. Each tray contains 442 cells connected in series to produce a nominal bus voltage of 530V. The two trays are connected in parallel resulting in a 530V, 50kWh battery bank.
- Pulse Forming Network – An important question for hybrid electric platforms using high power advanced electric weapon systems is the interaction of the pulse power system used to fire the weapon system with the mobility, guidance, control, communication and other continuous power equipment in the vehicle. Within the SIL the Pulse Forming Network (PFN), which is, the power supply that provides the necessary electric power and pulse shape to fire electric weapon systems provides a simulation of the intense electrical environments of high power electrical weapon systems. The SIL PFN is composed of two parts, the capacitor bank that stores the energy and provides the very high power output pulse and the charger that charges the bank. The charger is capable of charging the PFN in a few seconds. The PFN has the capability of firing two loads with completely different electrical characteristics. An Electromagnetic Armor (EMA) load that requires relatively high current (~MA) short duration pulses (~100μs) and an Electrothermal Chemical (ETC) load that requires a relatively low current (~100 kA) long duration pulses (~0.5ms). To accommodate these disparate loads the PFN is composed of two capacitor banks storing 100kJ each. Each bank has eight 250 μF, 10kV capacitors either one of which can be fired independently. The ETC load is designed to simulate a 60mm ETC gun and can fire up to five consecutive shots. This is a laboratory device that simulates an ETC gun autoloader. The firing rate depends on the charging rate. The existing charger in the SIL will provide a firing rate of 1shot /10s or 0.1 Hz.

Figure 7 shows schematically the Phase III simulator built on integration of the P&E SIL with the motion base/crew station at the GVSL. This phase builds on the preceding phase using the power system model from Phase II integrated into the GVSL motion base. The major addition in capability of this phase is the installation in the P&E SIL of the high resolution vehicle model used in the crew station to calculate the vehicle loads for the SIL dyno.

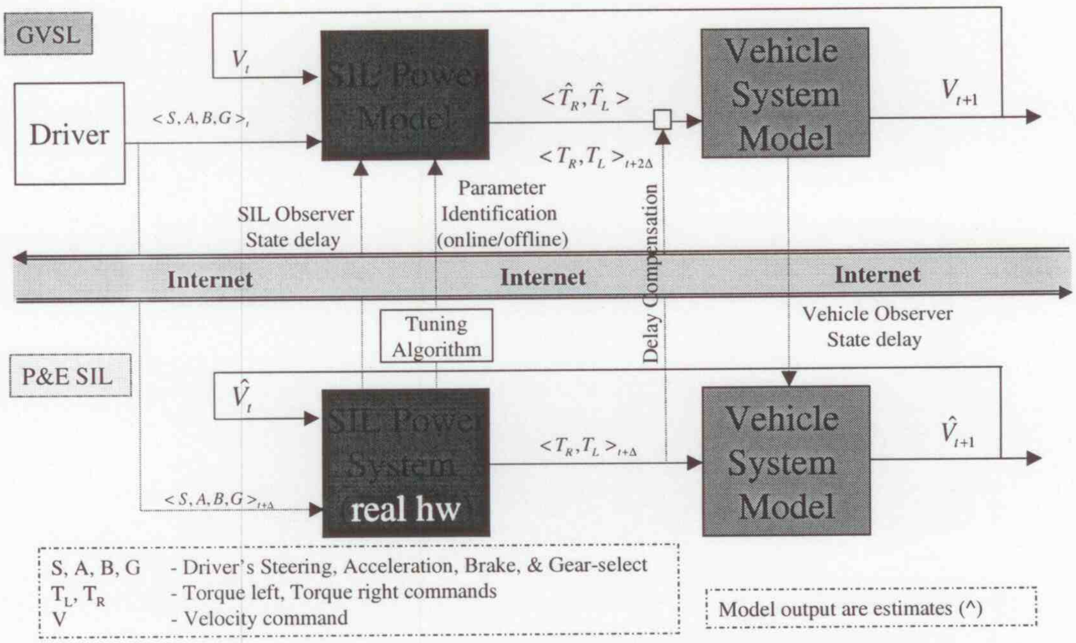


Figure 7 – Conceptual layout of integration of the hybrid electric SIL with the motion platform and crew station at the GVSL.

Our goal in this phase is to provide instantaneous feedback to the driver and commander as they perform tasks in the crew station. Their responses will be captured and used as the basis for high resolution mission profiles. In the process, by linking the SIL with the GVSL the SIL becomes a component in a DIS-compliant system.
The major issue with this phase is the physical distance separating the SIL and the GVSL. With signal propagation times on the order of 100 ms operating the two so that there is closed loop control of one with the other is a technical challenge. We are attacking this problem by having system simulations running on both ends of the connection simulating the hardware at the other end. For example, at the GVSL we have a simulation of the hardware at the SIL running at the GVSL. The simulation gives real-time input to the crew station that is used to drive the high-resolution vehicle model and provide feedback to the driver and commander. Error correcting and real-time parameter estimation code is inserted both at the SIL and the GVSL to correct and update the simulations operating the hardware at both ends of the connection.

Before implementing the system we are performing a significant simulation effort to ensure that the parameter estimation and error correcting codes can indeed be used to remove the communication transport delay and allow real-time control of the SIL from the GVSL. At the present time we have performed detailed simulations of the GVSL/SIL with the a GVSL simulation operating in one location and the SIL operating in another location to measure and quantify the time delay and its impact on the control of the simulations.

CONCLUSION

Through the use of modeling and simulation across a spectrum of resolutions, this effort is attempting to relate conceptual designs to operational effectiveness and provide an environment to a power system designer that allows for power management optimization by placing the conceptual system into as close an approximation of its future usage condition as is possible with today's modeling. The end result of this project is a desktop engineering analysis and design tool that has embedded within in high-resolution models of dynamic power generation and dynamic consumption devices, a table of loads required by static (or small) power consumption devices, along with a set of duty cycles that "drive" the models through various military scenarios. In addition, the end result includes the capability to export the models to real-time simulation systems that allow operator and hardware in the loop experiments and design analyses, along with the capability to like the design level representations to typical military operational simulation software packages.

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